TECHNICAL BULLETIN NO. 51 JUNE 1963

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ACKNOWLEDGMENT

This research was supported by funds provided in a contract between the University of Hawaii and the Tennessee Valley Authority, Contract No. TV21132A.

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Effects of Silicates on Phosphorus Availability to Sudan Grass Grown on Hawaiian Soils[1]

ROBERT H. SUEHISA, O. R. YOUNGE, and G. DONALD SHERMAN

INTRODUCTION

The low efficiencies encountered in phosphorus utilization by agronomic crops grown in some Hawaiian soils are allegedly due to the high phosphorus-fixing capacity of the soils. To maintain a balanced supply of phosphorus available as a nutrient for the plant, abnormally high rates of phosphate fertilizers apparently must be applied. Therefore, a study concerning reduction in the fixative power of lateritic soils through the use of silicon should be beneficial to improving the efficiency of phosphate fertilizers.

Before phosphorus fixation can be controlled, considerable attention must be given to the conditions under which it exists and to the actual mechanism of the fixation process, a prime factor of which is the availability of phosphorus material in the soil. Phosphate fertilizers, which provide this material, vary in water solubility and this affects the rate at which the phosphate ion can be fixed by the soil or utilized by the plant. The availability of the phosphorus material is also determined by the amount and the chemical form of the material, together with its particle size. Differences in soil characteristics also affect availability. Products formed when a phosphorus carrier goes into solution in the soil water are governed by soil factors, the most important apparently being the chemical nature of the soil minerals. The relative abundance of fixative agents such as amorphous sesquioxides, kaolinite, halloysite, montmorillonite, calcium carbonate, and ionic aluminum and iron, may also determine the magnitude of fixation. Phosphorus materials tend to combine with these agents through ionic reaction, displacement, or surface adsorption and absorption, and the end products which form cannot be readily utilized by plants and are therefore said to be fixed. Phosphorus reaction products are thus formed in the soil. The degree of solubility of the initial, intermediate, and end products is further governed by pH, moisture, temperature, coexisting ions, and mineral composition.

[1] This technical bulletin is part of a thesis submitted by the senior author to the Graduate School of the University of Hawaii in partial fulfillment of the requirements for the Master of Science degree.

To control phosphorus fixation, the activity of the fixing agents must be so reduced that only minimum combination with phosphorus occurs. A change in pH associated with applications of lime to acid soils shifts the equilibrium to a position where the phosphorus remains more available. Exchange of cations and anions on the soil complex influences the amount of phosphorus in solution. Decreasing the active aluminum and iron also keeps the phosphorus available for utilization by plants. In some instances silicon amendments, besides the use of lime, have made phosphorus more available to the crop and have thus increased yields.

Results of past experiments suggest that a study of the role of soluble silicates on the availability of soil phosphorus or on the reduction of phosphorus-fixing power of the soil may contribute much to increase the efficiency of phosphate fertilizers in lateritic soils. In Hawaii, there is a need for study of the utilization of new high-analysis phosphate fertilizers with varying degrees of water solubility. The objectives of this research are, therefore, a study of the effects of silicon-containing materials on lateritic soils in relation to crop yield, the silicon-phosphorus ratios in plant tissue, the solubility characteristics of applied phosphates, soil reaction products, and the nature of soil minerals.

REVIEW OF LITERATURE

TVA-produced phosphorus sources have undergone extensive evaluation throughout most areas of the United States. The behavior of the various soluble phosphate fertilizers apparently differs in acid and in calcareous soils (Terman and Stanford, 1960). In calcareous soils, the effectiveness of applied phosphates is influenced by fertilizer solubility, moisture condition, granule size, and method of application (Schmehl *et al.*, 1955). The degree to which the factors affect utilization of the phosphorus by crops varies in different localities, but, in general, it is controlled by the moisture regime. A general grouping of phosphate fertilizers based on the amount of water-soluble phosphorus is shown in *Crops and Soils* (1959). The most soluble of the solid phosphate fertilizers includes the superphosphates (ordinary and concentrated) and the ammonium phosphates, and in these from 75 to 100 percent of the total phosphorus is water soluble. Variations in the degree of ammoniation of superphosphates affect the water-soluble phosphorus and generally decrease as the N:P ratio narrows. The least soluble phosphates are the metaphosphates, dicalcium phosphate, rhenania phosphate, and rock phosphate, in which only a small percentage or almost none of the total phosphorus is water soluble.

Early work done on fixation of added phosphates in Hawaiian soils by Ayres (1934) showed that nearly all of the soils tested were capable of exhibiting this phenomenon. Davis (1935) attributed this to an absorption effect of the soils rather than to adsorption by gels present in the soils. Chu and Sherman (1952) found that the prevalence of hydrated sesquioxides in certain soils caused more than 90 percent of the moderate amounts

of added phosphorus to be fixed in an insoluble form in a relatively short period of time. When the oxides were removed, less than 30 percent of the applied phosphorus was fixed. The latosolic soil groups apparently exhibit the highest phosphorus-fixing capacities. Kaolinite present in the Low Humic Latosols and Humic Latosols also fixes phosphorus to a considerable extent. The mechanism of this fixation by kaolinitic clays has been attributed to the aluminum associated with lattices (Low and Black, 1947; Russell and Low, 1954; Kittrick and Jackson, 1955; Hemwall, 1957). Members of the montmorillonite and mica groups fix phosphorus to a lesser extent than do the other aforementioned components in Hawaiian soils. Ionic and surface precipitation of phosphorus by aluminum and iron compounds in the soil has not been studied to any great extent in Hawaii.

McGeorge (1924) suggested gibbsite as the main source of soluble aluminum in most Hawaiian soils. Low and Black (1947) reported that, when kaolinitic and halloysitic clays were present, the addition of phosphates to the soil system resulted in inducing the decomposition of the clays and in subsequent precipitation of the aluminum as aluminum phosphate and release of soluble silica. Hemwall (1957) also concluded that the phosphorus became fixed by reacting with the soluble aluminum originating at the exchange sites or from lattice dissociation and formed a highly insoluble aluminum phosphate compound. Perkins *et al.* (1957) found a correlation between the amount of phosphorus fixed and the solubility of the aluminum when kaolinite was ball-milled in the presence of phosphates.

The insoluble phosphorus fractions formed upon hydrolysis of applied phosphate fertilizers have been studied in considerable detail. Terman and Stanford (1960) demonstrated that, as dissolution of fertilizer particles progresses and subsequently releases phosphate ions, a saturated solution, with respect to phosphorus, arises in the vicinity of the particles. Such an acidic reaction brings large quantities of reactive aluminum, iron, calcium, and magnesium, and other soil constituents rapidly into solution in the zone immediately surrounding the granule. The products formed in acid soils are related to the variscite-barrandite-strengite isomorphous series and, where ammonium and potassium are present, the taranakite-like forms of phosphate also occur. These taranakite forms are utilizable by plants and are not considered end products, but intermediate types. Products of the isomorphous series are the least soluble of the forms in acid soils. In calcareous soils, the basic reaction results in the precipitation of nearly insoluble forms of calcium phosphate.

The mineralogical character of soil and of synthetic phosphate products has been studied by using petrographic and X-ray instruments (Haseman *et al.*, 1950; Lindsay *et al.*, 1959). The phosphate reaction products of iron and aluminum have also been evaluated as sources of phosphorus for plants (Huffman *et al.*, 1960; Taylor *et al.*, 1960).

Recent work by Hsu and Jackson (1960) indicated some phosphorus transformations involving iron and aluminum occur during soil genesis.

The stability of the reaction equilibrium is influenced by the phosphorus, aluminum, and iron concentrations, and by the pH of the system. The interrelationships between these constituents are reflected in the distribution of the inorganic phosphorus fractions found in the soil. Chang and Jackson (1957) outlined a procedure for identifying discrete phosphorus particles, surface-precipitated discrete phosphates, and occluded phosphates, by utilizing specific reagents for extraction. Hawaiian soils contain high quantities of iron and aluminum present as various mineralogical compounds. Identification of each of these minerals was made by Tamura and Jackson (1953) and Tamura *et al.* (1953) employing spectrographic, X-ray, and differential thermal analysis methods. Transformations of iron and aluminum oxides occur under a wide range of conditions and the equilibrium existing between the various inorganic constituents shifts according to the predominantly influencing external and internal factors.

Under conditions where phosphorus or lime is applied, one may expect that a change in the equilibrium will occur according to Le Chatelier's principle. Hsu and Jackson (1960) reported that the rates of the processes were controlled by the slow rates of ion diffusion along moisture films joining particles of different species. Liming acid soils was found to decrease the soluble aluminum content (Schmehl *et al.*, 1950; Shoop *et al.*, 1961). Robertson *et al.* (1954), using oats and corn as the test crops, found, after application of lime to soils with wide ranges in pH level, that the sesquioxide content influenced the availability of phosphorus from soils with low residual phosphate. In the presence of high amounts of sesquioxides liming improved phosphorus availability, but where the sesquioxide content was low, liming was ineffectual. It is apparent that the alterations in the soil equilibrium following applications of phosphorus and lime reflect on the solubilities of the various inorganic constituents and thus a study of the phosphorus-silicon interaction, from this point of view, needs consideration. Raupach and Piper (1959) reported that in high sesquioxide soils, there is a probability that the increase in available phosphorus with increasing pH causes a change in the equilibrium constants due to changes in the concentration and degree of crystallinity, and to partial substitution of other ions in the iron and aluminum phosphates.

The theories concerning phosphorus-silicon interaction in soils are numerous. The mechanisms governing the availability of phosphorus to plants have not been conclusively established as specific modes of action within the plant, in the soil, or at the soil-root interface. A survey of literature illustrating the agronomic aspects of silica in relation to phosphorus uptake was made by Taylor (1960). Although response to silicon in terms of the yield status of the test crop has been obtained under quite a number of environmental conditions, it is the indirect effect of silicon on the improvement and efficiency of phosphate fertilizers that is of greatest interest.

Although high amounts of silicon were assimilated and accumulated by the plant when silicates were applied to the soil (Toth, 1939; Whittenberger, 1945; Bastisse, 1950; Raleigh, 1953), it appeared that the silicon-

phosphorus ratio in the plant tissue is determined to a great extent by the level of available phosphorus in the soil. Hall and Morison (1906) and Fisher (1929) showed this ratio increased with silicate application, but the latter worker found the attribution of silicon to the increased yield was less when phosphorus was present than when it was not and silicon was applied alone. Raleigh (1953), working on a wide range of soils, reported increased uptake of phosphorus with sodium and potassium silicate applications occurred only on soils where phosphorus levels were deficient for crop growth. DeDatta (1958) showed improvement in the yield and phosphorus status of berseem followed high applications of sodium silicate to Indian soils.

Improvement in the soil physical condition upon application of silicon, which led to a better utilization of phosphorus, was reported by Duchon (1925). Beneficial effects of calcium silicate as a liming agent and as a source of calcium were obtained by Schollenberger (1922), Barnette (1924), and Blanck *et al.* (1936). Raleigh (1953) observed that sodium and calcium silicates were more effective in increasing phosphorus availability than was potassium silicate at low phosphorus levels. Dix and Rauterberg (1934) and Noda and Saito (1952) showed there was an improvement in phosphorus utilization when colloidal silica was used as an amendment with phosphorus applications. Akhromeiko (1934) reported that the diffusion of phosphorus increased when in the form of a SiO_2-P_2O_5 complex at the soil solution–root interface. Sreenivasan (1934) attributed an increase in the phosphorus availability to the peptizing action of colloidal silica. Gile and Smith (1925) concluded that silica gel exerts a solvent action on the phosphorus and thus renders it more available.

Many workers (Hall and Morison, 1906; Schollenberger, 1922; McGeorge and Breazeale, 1924; Gile and Smith, 1925; Scarseth, 1935; Toth, 1939; Kelly and Midgley, 1943; Dewan and Hunter, 1949; Laws, 1950; Noda and Saito, 1952; Albritton and Ellis, 1957; Taylor, 1960) have held the anionic exchange in the soil of silicate for phosphate ions as the cause of improved phosphorus uptake and yield. Mattson (1931) found that the phosphate ion strongly displaces the silicate ion but apparently there is not a reverse displacement of the phosphate ion by the silicate ion. Iler (1955) mentioned that gelling of sodium silicate is greatest when the pH ranges from 5.0 to 8.0, and that silica gel has no ionic character below pH 7.0. A thorough compilation of the chemistry of silica and of soluble silicates was made by Iler.

Sreenivasan (1935, 1936) found oxide gels of iron and aluminum adsorbed silicate and phosphate ions but the retention of KH_2PO_4 decreased when the soil was pretreated with sodium silicate. Toth (1937) reported similar adsorption effects in phosphated and silicated hydrated gel systems. Taranovskaya (1941) noted calcium and magnesium silicates were more effective than lime in mobilizing phosphorus and in reducing the soluble aluminum content. Reifenberg and Buckwold (1954) noted the displacement of silicate for phosphate ions was in the order of zero magni-

tude when the pH was decreased to 4.0. Bastisse (1946, 1950) also found silica increased the solubility and availability of phosphorus in iron and aluminum hydroxide systems.

In Hawaii, Sherman *et al.* (1955) reinvestigated McGeorge's (1924) suggestion that applications of soluble silica influence the phosphorus uptake of plants. The response was measured in Sudan grass by pot trials and the plant tissue analyzed. Previous work by Sherman *et al.* supported their conclusion that increased phosphorus assimilation in the presence of silicates, as shown in Sudan grass grown on a Humic Latosol (Honolua series), was associated with the mineralogical composition of the soil. In contrast, Sudan grass grown on Low Humic Latosols, Dark Magnesium Clays, and Humic Ferruginous Latosols showed no beneficial response to silicate applications. Ikawa (1956) noted a reduction in the phosphorus-fixing capacity in a representative soil of the Humic Latosol followed applications of silicon. A fairly elaborate study of phosphorus-silicon interactions was made in Australia by Raupach and Piper (1959) using a high phosphorus-fixing Seddon soil in pot and laboratory experiments. They found in the pot trials that the use of silicates increased phosphorus efficiency, but the effect did not last for more than a year. In the laboratory, solutions of potassium chloride and calcium chloride having similar ionic strength were shaken together with Seddon soil in separate systems having different pH levels. The greatest amounts of phosphorus were detected in the solutions when both phosphorus and silicate were added to each of the potassium chloride and calcium chloride systems. More phosphorus was left in solution as the pH increased above 5.0 in the KCl system, but the solubility of the calcium phosphates controlled the amount of phosphorus remaining in solution in the $CaCl_2$ system. The authors emphasized the role of aluminum and its effect on the silicate solubility curves. Silicon did not appear to change the type of reaction by which phosphorus is fixed but, instead, appeared to alter the equilibrium constants involved.

To clear ambiguity in the usage of the terms "silica" and "silicates," "silicon" will be used throughout this paper as a general term for all materials containing the latter. Taylor (1960) grouped the silicon-containing materials into four classes: colloidal silica and soluble silicates of sodium, potassium, calcium, and magnesium; calcium silicate slags containing less than 10 percent P_2O_5, which are by-products of blast- and electric-furnace processes; silico-phosphate fertilizers and basic slags containing about 30 percent P_2O_5; and silicyl phosphates, products of the reaction of phosphoric or superphosphoric acid with finely divided silica.

EXPERIMENTAL MATERIALS AND METHODS

Field and pot studies were conducted on soils having low, medium, and fairly high total silica content and representative of the latosolic great soil groups. The soils chosen also varied in their mineralogical content and were therefore capable of fixing varying amounts of applied phosphates. For the

pot studies, the transported soils were protected from dehydration and possible losses of cation exchange capacity. A total of three soil types was investigated for response to silicon applications.

Soil of the Wahiawa series, representative of the Low Humic Latosol group, was taken from the Poamoho area for the pot studies, and is designated Poamoho soil in this report. This area receives about 40 inches of rainfall annually. Kaolinite (45–55 percent, including halloysite), hematite (15–25 percent), allophane (5–10 percent), and montmorillonite (5–15 percent) were found by Tamura *et al.* (1953) to be the chief minerals in the Low Humic Latosols. This soil also contains some illite. Ayres *et al.* (1946) found Napier grass utilized the potassium slowly during a long-term field experimental study. Chu and Sherman (1952) demonstrated that the amorphous iron oxides in this soil were not the only cause of phosphorus fixation, as removal of the iron compounds by tartrate treatment still showed that 30 percent of the phosphorus was fixed by the remaining fraction containing kaolinitic and halloysitic clays. High amounts of manganese dioxide, which is a dominant characteristic of this great soil group, persists throughout its profile. The topsoil, which contains about 30 percent SiO_2, has a pH of 5.2. Kanehiro and Chang (1956) found the top 0 to 10 inches of soil had a cation exchange capacity of 17.8 meq. per 100 gm. and a base saturation of 53.4 percent. Matsusaka and Sherman (1950) showed this soil possessed a low buffering capacity, while data from Uehara and Sherman (1956) showed the amounts of organic matter and of clay separate were 3.4 percent and 55.8 percent, respectively. Previously, the Poamoho soil had not demonstrated any beneficial response to phosphorus-silicon treatments when it was investigated by Sherman *et al.* (1955).

Soil of the Honolua series, representative of the Humic Latosol great soil group, was taken from the Helemano area. This area receives 80 inches of rainfall annually. Tamura *et al.* (1953) identified the minerals present in a representative soil of this series as kaolin (15–20 percent), gibbsite (15–20 percent), hematite (20–25 percent), goethite (10–20 percent), montmorillonite (5–10 percent), interstratified 2:1 layer silicate (5–10 percent), mica (1–5 percent), and quartz (1–5 percent). These authors found also a lesser amount of illite than that present in the Poamoho soil. Chu and Sherman (1952) reported that about 88 percent of the applied phosphorus was fixed by the hydrated sesquioxides. Very granular A-horizon and water-stable aggregates are noteworthy characteristics of this soil. Kanehiro and Chang (1956) reported that the cation exchange capacity, 33.5 meq. per 100 gm., increased with the breakdown of kaolinite and decreased considerably upon dehydration. They also found that changes in the soil, brought about by continuous cultivation, resulted in a 28 percent loss in the cation exchange capacity of this soil as compared to its virgin counterpart. The total silica content is slightly less than that in the Poamoho soil, ranging from 15 to 25 percent SiO_2 in the topsoil. Matsusaka and

Sherman (1950) found the pH highly acid (4.5) and the buffering capacity relatively high.

A field station of the Hawaii Agricultural Experiment Station provided the site for obtaining a soil possessing a low content of total silica. The site was at the Wailua Game Refuge, Kauai; it is currently being used for reclamation of the stripsoil remaining after bauxite mining (Younge and Moomaw, 1960). This area receives 75 inches of rainfall annually. Sherman (1958) reported this soil as a Kapaa clay, which is classified in a new great soil group, the Aluminous Ferruginous Latosol. The aluminum content of this soil group is high and predominates as crystalline gibbsite aggregates throughout the soil profile. Sherman discussed also the mode of formation leading to the stability of alumina. The silica content of bauxitic soils is quite low and ranges in general from 1 to 3 percent. The alumina content ranges from 15 to 55 percent Al_2O_3, and the remaining material is mostly iron oxides and hydrates. Younge and Fujimoto (unpublished data) found the cation exchange capacity of the topsoil and stripsoil was very low, only 7.7 meq. per 100 gm. It was shown that the buffering capacity of the stripsoil is lower than that of the topsoil, as only 5000 pounds of $CaCO_3$ per acre 7-inch layer were needed to raise the pH of the stripsoil from 5.0 to 6.2, whereas for topsoil, 10,000 pounds of $CaCO_3$ per acre were required to obtain the same pH change. The native topsoil contains 4 to 6 percent of organic matter and this accounts for the high buffering capacity.

The phosphate fertilizers used throughout the study were supplied in part by the Tennessee Valley Authority and were obtained in part through commercial sources. A description of the fertilizer materials used is given in table 1, and they are usually referred to in the text by the appropriate symbol designations. The sources of silicon were sodium metasilicate, calcium silicate, and silica gel, the former only being used under field conditions because of its availability commercially. Reagent-grade calcium silicate and silica gel were used for pot studies.

The essential elements, N, K, Mg, Mn, Zn, Mo, and B, were applied as a blanket treatment at optimum rates in the form of a commercially mixed basic fertilizer for the field work and as nutrient solutions in the pot studies. The liming material for the field tests was coral limestone and for the pot tests, hydrated lime. Sudan grass, California No. 23, was used as the test crop in all experiments because of its fast maturing qualities and its response to phosphorus. The field experimental design consisted of treatments randomized in blocks, with six replications. The treatments were randomized to eliminate positional effect, with four to five replications made in each of the pot studies.

For each harvest, yield data were collected and statistically analyzed for least significant differences at the 5 percent and 1 percent levels of significance. Dry matter samples were composited for each treatment and analyzed for total phosphorus and silicon after wet digestion. The phosphorus was determined colorimetrically by the molybdivanado-phosphoric acid yellow color method of Kitson and Mellon (1944), and the silicon was

TABLE 1. Description of phosphate fertilizers used for phosphorus-silicon interaction studies on Hawaii soils

SYMBOL DESIGNATION	MATERIAL AND U.S. SCREEN NO.	TVA MATERIAL NO.	LABORATORY NO.	CHEMICAL COMPOSITION, PERCENT						
				P				Ca	Cl	CO_2
				P	Total P_2O_5	Available	Water Soluble			
CSP	Concentrated Superphosphate 0–49–0	291	67,595	21.7	49.8	49.4	45.3	14.7	–	–
DCP	Dicalcium Phosphate 0–48–0 –12 mesh	238	56,846	21.1	48.4	47.9	0.5	28.0	–	–
CMP	Calcium Metaphosphate conditioned with limestone 0–62–0 –12 mesh	333	72,845	27.9	64.0	62.0	–	19.7	–	0.2
DAP	Diammonium Phosphate[1] unconditioned 21–53–0	345	–	23.1	53.0	53.0	–	–	–	–
KMP	Potassium Metaphosphate[2] 0–47–38 –3/8" to +4" mesh	326	63,743	22.9	52.6	47.4	–	–	4.8	–
SP	Silico-phosphate –6 mesh	–	19,788	21.2	48.6	47.4	9.3	–	–	–
AP	Ammophos[3]	–	Commercial	21.1	48.4	48.4	48.4	–	–	–
RP	Raw Rock Phosphate	–	Commercial	16.0	36.7	0.0	0.0	36.2	–	–

[1] Total nitrogen, 21.0 percent.

[2] Total potassium, 32.3 (K_2O, 38.9) percent; water-soluble potassium, 10.8 (K_2O, 13.0) percent.

[3] Total nitrogen, 11.4 percent.

determined gravimetrically after repeated washing with hot 10 percent HCl.

In general, the control and treated soil samples were analyzed for 0.02 N H_2SO_4-extractable phosphorus, which is the "available" phosphorus defined by Ayres and Hagihara (1952), by means of the molybdenum blue color developed with $SnCl_2$ as described by Jackson (1958). Other determinations were made for soluble silica reaction (Bonnet, 1939) by glass electrode pH meter, aluminum phosphate fraction (Chang and Jackson, 1957), and extractable aluminum by the aluminon method. X-ray and differential thermal analysis methods were employed to note any changes in mineralogical composition following treatments of phosphorus and silicon to specific soils.

Field experiment 1: An old, abandoned, weedy pineapple field site at Helemano, Oahu, was prepared for planting in March, 1960. The treatments were phosphorus, as dicalcium phosphate, monoammonium phosphate, and rock phosphate, applied broadcast at a probably deficient level of 250 pounds P per acre. Sodium metasilicate ranging from 0 to 2000 pounds Si per acre was applied in combination with phosphorus. Coral limestone at 6000 pounds per acre and the basic treatments of nitrogen, potash, and molybdenum were then broadcast and disced into the soil. The treated plots were seeded to Sudan grass No. 23 in May, 1960, with a John Deere fertilizer-seeder attachment, in rows 7½ inches apart, 1½ to 2 inches in depth, and at a rate of 8 to 9 seeds per foot of row. The first crop was harvested at the heading stage in July, 1960, and the second in September, 1960. No additional nitrogen was added for the second crop, and nitrogen deficiencies were demonstrated in the form of reduced yields at the second harvest.

Field experiment 2: A virgin bauxitic topsoil site at Wailua, Kauai, was prepared in March, 1960, for phosphorus-silicon applications similar to those used at Helemano. After the phosphorus-silicon treatments were applied, coral limestone and basic fertilizer treatments were disced into the soil. Sudan grass was seeded in April at the same spacing, depth, and rate as at Helemano. Four successive cuttings of Sudan grass were taken without additional applications of fertilizer. Leaf rust was prevalent on the grass throughout the entire experiment because the prevailing temperatures and high relative humidities present were highly favorable to plant diseases.

Field experiment 3: A test site on bauxite stripsoil, the exposed surface remaining after removal of commercial ores, in this instance about 14 feet below the original level, was established about a quarter of a mile from field 2. The field test was operated as that for field 2, but treatment was limited to the DCP series. The silico-phosphate reaction product was also tested for comparative purposes with DCP at the same phosphorus level. This experiment, as with the preceding, was developed on plots measuring 5 feet by 7 feet, which were smaller than those at the Helemano site. Four cuttings of Sudan grass were made prior to termination of the tests.

Pot experiment 1: This pot experiment covered the range in solubility and the amounts of phosphorus utilized by Sudan grass in previous tests from various TVA and commercial phosphate fertilizers. Both Helemano and Poamoho topsoils were used in this study. Replicated treatments were applied on the surface and then mixed into the top 3 inches of soil placed in 2-gallon pots. Hydrated lime was applied to bring the soil pH up to 6.2. Prior to seeding, the basic elements were applied in solution. One week after emergence the Sudan grass seedlings were thinned to 10 plants per pot. Four successive cuttings of Sudan grass at the heading stage were taken from the Helemano test and three from the Poamoho test. Nitrogen in the form of urea was added after each harvest.

Pot experiment 2: Dicalcium phosphate and sodium metasilicate were applied at various rates to the Helemano soil in Mitscherlich gallon-sized pots. The replicated treatments were mixed with the top 3 inches of soil and the pots seeded to Sudan grass 1 week later. The stand was thinned to five plants per pot. After each cutting, nitrogen was added at the rate of 200 pounds per acre in nutrient solution.

Pot experiment 3: Dicalcium phosphate at two levels and varying rates of calcium silicate and silica gel were applied together in order to observe their influence on yield and phosphorus uptake by Sudan grass grown on Helemano soil. Procedures used were the same as in the previous pot tests. The rates of silicon were increased tenfold at each step to obtain a wide range of effects. Four cuttings of the test crop were made, and nitrogen was applied for each crop as in the previous pot tests. The highest level of calcium silicate was found not completely dissolved at termination of the experiment and therefore was not included in the soil analysis.

Pot experiment 4: A detailed study of the TVA-produced silico-phosphate reaction product was made using the Poamoho soil, with and without hydrated lime, in 2-gallon pots. Other sources of lime, i.e., calcium silicate and calcium silicate combined with SP, were also evaluated. The various lime materials were applied at rates according to specific neutralizing requirements and therefore the total applied silicon rate varied. Five Sudan grass plants were grown in each pot. The experimental procedure followed was similar to that of previous pot work.

Pot experiment 5: Various phosphate fertilizers were applied with varying rates of silicon as calcium silicate and sodium metasilicate on Poamoho topsoil. No form of lime was added to the soil. In the data, differences in yield may be noted with similar treatments in the calcium silicate and sodium metasilicate series; these were a result of differences in planting dates and length of growing period.

RESULTS AND DISCUSSIONS

Preliminary investigation on phosphorus availability from various phosphate fertilizers. Pot studies were conducted on the efficiency of applied

TABLE 2. Performance of Sudan grass in pot trials and the efficiency of applied phosphate on Helemano and Poamoho topsoils[1]
(Pot Experiment 1)

P CARRIER	DCP	CSP	SP	DAP	KMP	CMP	RP	CK
Helemano soil[2]								
Total DM yield (gm/pot)	81.1	76.0	71.4	71.1	68.9	67.4	31.4	1.2
Total P uptake (mgm/pot)	212.9	221.0	178.3	172.6	201.8	165.7	35.5	1.7
P efficiency, %	5.5	5.7	4.7	4.5	5.2	4.3	0.9	—
Poamoho soil[3]								
Total DM yield (gm/pot)	87.7	89.0	75.0	91.9	—	90.3	71.7	51.3
Total P uptake (mgm/pot)	113.3	116.6	87.3	106.1	—	108.3	71.4	48.7
P efficiency, %	22.2	22.7	16.9	20.9	—	21.1	14.0	—

[1] Four replications, yield composited for chemical analysis.

[2] Return for four successive cuttings of Sudan grass, for treatments of P at 1000 lb/acre.

[3] Return for three successive cuttings of Sudan grass, for treatments of P at 250 lb/acre.

P so that a choice of fertilizers, suitable for the various soils under consideration, could be made for the study of phosphorus-silicon interaction. On the Helemano soil, DCP showed the highest yield, followed by CSP, SP, DAP, KMP, CMP, and RP in decreasing order. In general, the yields did not vary appreciably among the various sources of P, except for low production in the slightly soluble rock phosphate treatment (table 2). For the Helemano soil, the total P uptake per pot for four successive cuttings of Sudan grass indicated CSP, DCP, KMP, SP, DAP, CMP, and RP supplied P in decreasing order. It was necessary to apply an abnormally high rate of P to this soil, as it is capable of fixing at least 90 percent of the P if applied in low amounts. The data show the P recovery was good, but because of the high P rate used, the percentage of recovery was naturally low. For the Poamoho soil, DCP, CSP, DAP, and CMP were nearly equal in performance. Rock phosphate was an inferior product on this soil. The check pot showed growth of Sudan grass was satisfactory in comparison to growth on the Helemano soil, which was poor.

Progressively higher P content in the plant tissue was obtained with successive cuttings when DCP, CSP, CMP, KMP, and SP treatments were added, but in the DAP-treated pots, the initial harvest showed an abnormally high P content which then declined with further harvests. Apparently, the P was released to the plant at a slow rate initially which then,

in the case of the soluble phosphates, increased with time. In general, DCP and CSP were superior sources of P in both soils, and RP was the poorest source. Signs of P deficiency were prevalent in the form of reduced yields and in the purpling of leaves of Sudan grass grown on both soils after the second cutting. Evidently, the P efficiency did not increase to a great extent after the second cutting.

EFFECT OF SILICON IN HELEMANO SOIL

Effect of silicon sources on yield, phosphorus uptake, and chemical composition of Sudan grass grown on Helemano soil. Field experiment 1 showed sodium metasilicate greatly increased Sudan grass yields whether P was present or not. Table 3 shows significant increases in yield were obtained in the first and second cuttings of Sudan grass, but the yield was greatly affected by the water solubility of the P carriers. However, as was expected, the over-all yield was highest in the AP series for the first cutting. The yields were significantly increased when Si was applied together with P at 250 pounds per acre and at 500 pounds per acre. The yields were also significantly higher than when P was applied alone at 1000 pounds per acre. In the DCP series, all levels of application of silicon, up to an application of Si at 1000 pounds per acre, significantly increased dry matter yield. It is apparent in the first cutting of the RP series that all levels of Si applied with P at 250 pounds per acre improved yields, but the increase was statistically significant only at the 1000 pounds Si per acre level. In the No P series, yield increased threefold when Si was applied at 1000 pounds per acre.

In the second cutting, significant increases in dry matter yield were obtained at all levels of silicon applied as sodium metasilicate in the DCP and RP series. No significant changes were observed for the AP series, except when Si was applied at 2000 pounds per acre. In general, the improvement in yield shown in the DCP series was much greater than that in the RP series. It is interesting to note that the less soluble phosphate fertilizers are more effective than highly soluble ammonium phosphate in promoting yield when applied together with sodium metasilicate. On the basis of data obtained from two crops, the less soluble P carriers appear to have a greater lasting effect in supplying P than do the more soluble materials. No pronounced changes in dry matter yield were obtained in pot experiment 2, where a similar soil was used with greater variations in applications of P levels (table 4).

The total P uptake in pounds of P per acre for two successive cuttings of Sudan grass showed definite increases over controls when silicon was applied, either with or without applied P (table 3). The curves presented in figure 1 illustrate the total amount of P assimilated by the two test crops for the various series. The magnitude of the percentage of increase over the controls in each series varied inversely with the solubility of the P carrier (table 3, column 9). The lowest increase was obtained in the

TABLE 3. Field trial on the effect of sodium metasilicate on yield and phosphorus uptake from three phosphate fertilizers by Sudan grass grown on Helemano soil (Field Experiment 1)[1]

TREATMENT, lb/acre		DRY MATTER YIELD, lb/acre			PHOSPHORUS UPTAKE, lb/acre			
P	Si	Total 2 crops	First cutting[2]	Second cutting[3]	Total 2 crops	First cutting	Second cutting	% Over control[4]
No P Series								
0	0	2084	1619	465	3.77	2.69	1.08	0
0	250	4181	3112*	1069	7.76	4.98	2.78	51.4
0	1000	7634	4986**	2648**	15.51	9.37	6.14	75.6
DCP Series								
250	0	5221	4443**	778	9.14	6.93	2.21	0
1000	0	7946	6273*	1673**	11.66	10.04	4.62	37.6
250	250	8438	6568**	1870**	16.14	11.17	4.97	43.3
250	500	8150	6291	1859	16.42	10.69	5.73	44.3
250	1000	8387	6238	2149	20.25	13.85	6.40	54.8
250	2000	8087	5218	2869	18.32	10.75	7.57	50.1
AP Series								
250	0	7562	5796	1766	11.65	8.11	3.53	0
1000	0	8354	6182	2172	13.59	9.64	3.95	14.3
250	250	9908	7852**	2056	18.40	14.29	4.11	36.7
250	500	10216	8114	2102	18.95	14.28	4.67	38.5
250	1000	8875	6935	1940	17.22	11.79	5.43	32.4
250	2000	7316	4760**	2556*	14.48	7.43	7.05	19.6
RP Series								
250	0	3348	2930	418	5.85	4.69	1.16	0
1000	0	4745	3607	1138*	8.91	6.13	2.78	34.3
250	250	5313	4163	1150*	10.28	7.08	3.20	43.0
250	500	5907	4165	1742	11.31	6.50	4.81	48.2
250	1000	8633	5566**	3067**	17.76	10.46	7.30	67.0
250	2000	6475	3873*	2602	13.01	6.82	6.19	55.0
L.S.D.[5]	0.05*		1392	629				
	0.01**		1836	829				

[1] Treatment replicated six times.

[2] 63 days growth, no foliar symptoms of nutritional deficiencies.

[3] 60 days growth, severe nitrogen deficiency limited yields.

[4] Total of two cuttings.

[5] The least significant difference required to prove a real difference between two treatments at the probabilities of 5 and 1 percent chance of error.

readily soluble AP series; the highest in the series receiving no P, followed closely by the series receiving rock phosphate. The soils receiving DCP were only slightly less responsive than the soils in the RP series, as the amount of water-soluble P was only slightly greater in the DCP series.

TABLE 4. Pot trial on the effect of sodium metasilicate and dicalcium phosphate in various combinations on yield and phosphorus uptake by Sudan grass grown on Helemano soil

(Pot Experiment 2)[1]

TREATMENT, lb/acre		DRY MATTER YIELD, gm/pot					PHOSPHORUS UPTAKE, IN DRY MATTER, mgm/pot				
P	Si	Cutting					Cutting				
		1	2	3	4	Total	1	2	3	4	Total
0	0	0.5	6.2	13.2	14.7	34.6	0.6	7.3	17.2	14.1	39.2
0	100	1.7	5.0	16.2	30.7	53.6	2.3	8.5	22.0	29.5	62.3
0	500	5.3	4.0	20.2	36.5	66.0	7.2	7.3	26.3	35.0	75.8
0	1000	3.7	2.2	14.7	30.0	50.6	5.0	4.1	19.1	28.8	57.0
100	0	8.0	5.7	21.0	34.5	69.2	12.8	13.1	30.7	38.6	95.2
100	100	8.3	4.0	21.7	31.5	65.5	13.3	10.2	32.1	35.3	90.9
100	500	4.3	2.8	26.0	26.5	59.6	6.9	7.2	43.7	29.7	87.5
100	1000	3.3	4.2	21.2	29.3	58.0	5.9	12.0	33.1	29.9	80.9
500	0	21.7	5.0	28.0	29.7	84.4	43.4	15.8	63.8	52.3	175.3
500	100	11.3	1.8	20.5	26.3	59.9	25.8	4.6	43.1	38.9	112.4
500	500	16.0	3.5	26.0	24.7	70.2	34.6	12.4	50.4	35.6	133.0
500	1000	11.7	4.3	25.5	35.3	76.8	24.6	12.9	52.5	44.5	134.5
1000	0	19.3	4.3	26.2	32.3	82.1	56.7	15.0	69.2	60.7	201.6
1000	100	20.7	4.2	22.3	33.6	80.8	57.1	16.4	58.9	72.6	205.0
1000	500	15.7	4.0	27.3	37.0	84.0	39.9	17.5	72.1	69.6	199.1
1000	1000	5.0	4.8	30.5	33.0	73.3	14.7	17.0	55.5	62.0	149.2
Growth Days		38	39	36	38						

[1] Yields of four replicates composited for analysis.

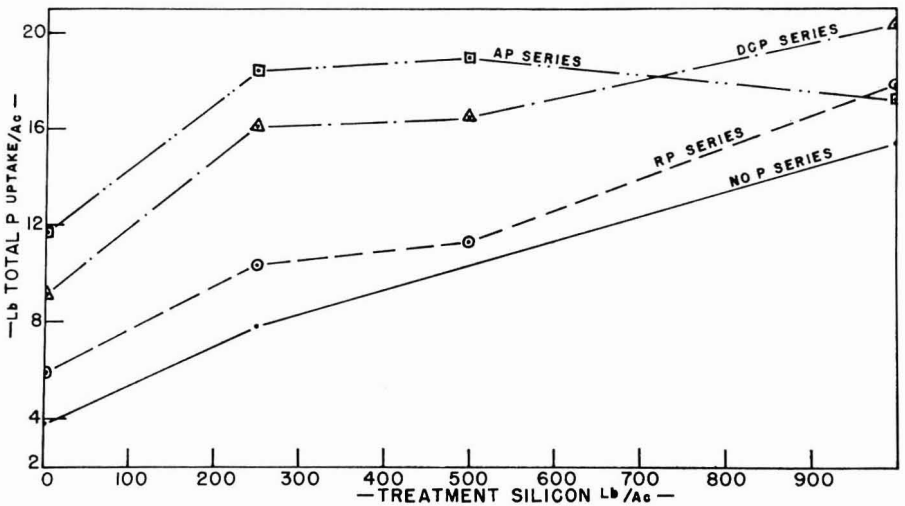

FIGURE 1. Effect of sodium metasilicate on total phosphorus uptake by two crops of Sudan grass grown on Helemano soil (Field Experiment 1).

Apparently, when P material applied together with sodium metasilicate has low solubility, the availability of P is increased to a greater extent than when silicon is applied together with a phosphate fertilizer that is highly soluble. In all cases, a larger amount of P was assimilated by the test crop upon silication than was assimilated when P was applied alone at 1000 pounds per acre. One to three times more P uptake occurred at all levels of silicon when P was applied at 250 pounds per acre than when P was applied alone at 1000 pounds per acre. The efficiency of applied P is greatly increased when silicon is also applied simultaneously to soils deficient in available phosphorus. In the absence of P, an application of Si at 1000 pounds per acre produced a 75.6 percent greater P uptake than that produced by the control, indicating improvement in the availability of the native phosphorus.

TABLE 5. Chemical composition of Sudan grass plant tissue grown at Helemano, Oahu, under various phosphorus-sodium metasilicate treatments (Field Experiment 1)[1]

TREATMENT, lb/acre		FIRST CUTTING			SECOND CUTTING		
P	Si	% P	% Si	Si/P	% P	% Si	Si/P
No P Series							
0	0	.166	.09	0.54	.232	.06	0.26
0	250	.160	.29	1.81	.260	.23	0.88
0	1000	.188	.50	2.66	.232	.56	2.41
DCP Series							
250	0	.156	.19	1.22	.284	.21	0.74
1000	0	.160	—	—	.276	.07	0.25
250	250	.170	.64	3.76	.266	.53	1.99
250	500	.170	.71	4.18	.308	.69	2.24
250	1000	.222	.75	3.38	.298	.94	3.15
250	2000	.206	.65	3.01	.264	.84	3.18
AP Series							
250	0	.140	.15	1.07	.200	.18	0.90
1000	0	.156	.11	0.71	.182	.11	0.60
250	250	.182	.49	2.69	.200	.42	2.10
250	500	.176	.65	3.69	.222	.55	2.48
250	1000	.170	.67	3.94	.280	.80	2.86
250	2000	.156	.78	5.00	.276	.82	2.97
RP Series							
250	0	.160	.41	2.56	.278	.29	1.04
1000	0	.170	—	—	.244	.05	0.20
250	250	.170	.58	3.41	.278	.54	1.94
250	500	.156	.71	4.55	.276	.56	2.03
250	1000	.188	.75	3.99	.238	.68	2.86
250	2000	.176	.64	3.64	.238	.67	2.82

[1] Yield of six replicates composited for chemical analysis.

It is evident from the field data (table 5) that the Si/P ratio increases greatly upon application of silicon, for whenever sodium metasilicate was applied abnormally high amounts of silicon were absorbed by the crop. Where no silicon was applied, less silicon was found in the plant tissue at the higher level of P than at the lower level. No appreciable differences existed in the percentage of Si between the first and second cuttings, but the percentage of P increased markedly in the second cutting. The Si/P ratios for Sudan grass in a pot test on the same Helemano soil gave considerably higher amounts of Si than in the field tests (table 6). No reason for the higher Si content of pot-grown Sudan grass appeared evident.

In pot experiment 3, Sudan grass grown on Helemano soil treated with calcium silicate exhibited superior growth performance over silica gel at similar rates of silicon in the presence or absence of phosphorus. In the absence of DCP, calcium silicate produced a gradual increase in dry matter yield which progressed to the highest level of applied silicon (table 7). The yield produced in the silica gel series remained essentially unchanged at all levels of silicon. When P was applied, the low levels of silicon in the silica gel series showed depressed crop growth which improved only slightly at the highest level of phosphorus. The beneficial effect at the highest level of silicon as silica gel was apparent only in the first of four harvests. Slight improvements in yield resulted when Si was applied at 100 pounds per acre and at 1000 pounds per acre in the calcium silicate series, but yields declined when Si was applied at 10,000 pounds per acre. In general, calcium silicate, in the presence of P, showed less improvement in dry matter yield than when applied alone. Silica gel remained essentially ineffective except at very high levels of application.

The P uptake generally varied directly with the yields produced in both series. Calcium silicate showed improved uptake of P whether or not phosphate was applied. Silica gel was without effect in promoting P uptake except at an application of 10,000 pounds of Si per acre. The silico-phosphate reaction product showed inferior performance to DCP alone and also when added to various silicon sources.

Plant tissue analysis of the dry matter revealed silicon absorption in the calcium silicate series was higher than in the silica gel series (table 8). The data show that the percentage of P remained relatively unaffected by the application of silicon. Apparently, the silicon-phosphorus relationship within the plant does not cause an imbalance of P to silicon, and it also appears to have had little effect on the yields in this pot test.

Effect of silicon sources on pH, extractable Al, and $AlPO_4$ fraction in Helemano soil. Where soluble silicate applications were applied in increasing amounts, analyses of both field and pot samples taken after termination of harvests revealed an increase in soil pH had occurred in each instance (fig. 2). The alkalinity produced by sodium metasilicate was much greater than that by calcium silicate, and the detrimental effects of the Na ion on plant growth showed up readily at the higher rates. Silica gel pro-

TABLE 6. Chemical composition of Sudan grass grown on Helemano soil treated with various rates of sodium metasilicate and dicalcium phosphate in pot trial

(Pot Experiment 2)[1]

TREATMENT, lb/acre		CUTTING											
		First			Second			Third			Fourth		
P	Si	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P
0	0	.126	0.72	5.71	.117	1.08	9.23	.130	.61	4.69	.096	0.97	10.10
0	100	.136	0.97	7.13	.170	2.00	11.76	.136	.48	3.53	.096	0.66	6.88
0	500	.136	1.35	9.93	.182	2.59	14.23	.130	.79	6.08	.096	0.93	9.69
0	1000	.136	1.22	8.97	.187	2.84	15.19	.130	.67	5.15	.096	1.32	13.75
100	0	.160	0.65	4.06	.230	1.46	6.35	.146	.41	2.81	.112	0.67	5.98
100	100	.160	0.81	5.06	.255	1.85	7.25	.148	.87	5.88	.112	0.63	5.63
100	500	.160	0.93	5.81	.256	2.88	11.25	.168	.74	4.40	.112	1.01	9.02
100	1000	.180	1.14	6.33	.285	2.77	9.72	.156	.85	5.45	.102	1.32	12.94
500	0	.200	0.44	2.20	.315	1.42	4.51	.228	.47	2.06	.176	0.82	4.66
500	100	.228	0.65	2.85	.256	1.33	5.20	.210	.44	2.10	.148	0.84	5.68
500	500	.216	0.84	3.89	.355	3.42	9.63	.194	.78	4.02	.144	1.32	9.17
500	1000	.210	0.81	3.86	.299	3.18	10.64	.206	.82	3.98	.126	1.34	10.63
1000	0	.294	0.49	1.67	.349	1.53	4.38	.264	.54	2.05	.188	0.67	3.56
1000	100	.276	0.58	2.10	.390	2.11	5.41	.264	.51	1.93	.216	0.76	3.52
1000	500	.254	0.95	3.74	.437	3.14	7.19	.264	.81	3.07	.188	1.13	6.01
1000	1000	.294	0.97	3.30	.355	3.20	9.01	.182	.90	4.95	.188	1.46	7.77

[1] Yields of four replicates composited for analysis.

TABLE 7. Pot trial on the effect of calcium silicate and silica gel, with and without phosphorus as dicalcium phosphate, on dry matter yield and phosphorus uptake by Sudan grass grown on Helemano soil

(Pot Experiment 3)[1]

TREATMENT, lb/acre		DRY MATTER YIELD, gm/pot					PHOSPHORUS UPTAKE, mgm/pot				
		Cutting					Cutting				
P	Si	1	2	3	4	Total	1	2	3	4	Total
No Si Series											
0	0	24.8	24.3	19.0	8.3	76.4	32.2	27.2	22.8	9.3	91.5
250	0	61.3	45.0	39.7	26.0	172.0	88.3	57.6	63.5	45.8	255.2
Calcium Silicate Series											
0	100	18.7	28.7	35.0	9.5	91.9	23.6	32.1	42.0	8.6	106.3
0	1,000	23.0	29.3	33.7	17.7	103.7	25.8	32.8	32.4	15.9	106.9
0	10,000	19.0	45.7	41.7	45.5	151.9	23.9	51.2	40.0	41.0	156.1
250	100	61.2	55.0	35.7	26.6	178.5	97.9	70.4	51.4	45.2	264.9
250	1,000	70.7	57.3	36.3	32.7	197.0	101.8	74.5	52.3	55.6	284.2
250	10,000	23.0	46.3	49.7	43.0	162.0	36.8	68.5	79.5	73.1	257.9
Silica Gel Series											
0	100	19.0	25.7	18.0	17.0	79.7	25.8	28.8	20.2	15.3	90.1
0	1,000	19.3	19.7	19.0	20.0	78.0	19.7	22.1	22.8	24.0	88.6
0	10,000	20.7	26.3	31.0	13.0	91.0	21.1	29.5	31.0	14.6	96.2
250	100	53.7	44.3	33.0	23.0	154.0	85.9	65.6	50.8	34.0	236.3
250	1,000	53.7	45.3	31.3	21.7	152.0	85.9	67.0	55.1	39.5	247.5
250	10,000	73.7	47.7	35.3	25.5	182.2	138.6	70.6	53.0	46.4	308.6
Silico-Phosphate											
250	266	35.2	45.0	34.0	18.0	132.2	54.9	57.6	49.6	29.9	192.0
Growth Days		45	40	45	43						

[1] Yield of four replicates composited for analysis.

duced a slight decrease in pH, possibly due to the formation of silicic acid. On addition of silicon, Raupach and Piper (1959) found the amount of P detected in solution increased with rising pH, even if the natural phosphates were present in small amounts.

Silicon applications decreased the extractable Al significantly, but had little effect in the presence of P (fig. 3). Miyake *et al.* (1924) observed the precipitation of silica together with some Al after mixing solutions of aluminum chloride and sodium silicate. Sodium carbonate, by causing a more alkaline condition, was more effective than sodium silicate in decreasing the Al in solution. McGeorge (1924) found in soil solutions relatively high in active Al that the increase in pH precipitated the Al as hydrosols. Raupach and Piper (1959) cited Raupach (1957) and Okamoto *et al.* (1957) as

TABLE 8. Chemical composition of Sudan grass plant tissue grown on Helemano soil treated with calcium silicate and silica gel, with and without phosphorus as dicalcium phosphate in pot trial

(Pot Experiment 3)[1]

TREATMENT, lb/acre		CUTTING											
		First			Second			Third			Fourth		
P	Si	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P
No Si Series													
0	0	.130	0.51	3.92	.112	0.72	6.43	.120	1.02	8.42	.112	0.90	8.04
250	0	.144	0.37	2.57	.128	0.61	4.77	.160	1.12	7.00	.176	0.71	4.03
Calcium Silicate Series													
0	100	.126	0.70	5.56	.112	1.02	9.11	.120	1.34	11.17	.090	0.95	10.56
0	1,000	.112	1.09	9.75	.112	1.17	10.45	.096	1.64	17.08	.090	1.41	15.67
0	10,000	.126	2.71	21.51	.112	1.93	17.23	.096	3.10	32.29	.090	2.50	27.78
250	100	.160	0.51	3.19	.128	0.60	4.69	.144	.88	6.11	.170	0.74	4.35
250	1,000	.144	1.05	7.29	.130	1.16	8.92	.144	1.36	9.44	.170	1.14	6.71
250	10,000	.160	2.21	13.81	.148	2.20	14.86	.160	3.42	21.38	.170	2.67	15.71
Silica Gel Series													
0	100	.136	0.63	4.63	.112	0.89	7.95	.112	1.35	12.05	.090	1.07	11.89
0	1,000	.102	0.79	7.75	.112	0.94	8.39	.120	1.43	11.92	.120	1.08	9.00
0	10,000	.102	1.55	15.20	.112	1.59	14.20	.100	1.94	19.40	.112	1.83	16.34
250	100	.160	0.65	4.06	.148	0.87	5.88	.154	1.25	8.12	.148	1.06	7.16
250	1,000	.160	0.72	4.50	.148	0.97	6.55	.176	1.31	7.44	.182	0.98	5.34
250	10,000	.188	1.14	6.06	.148	1.49	10.07	.150	2.03	13.53	.182	1.53	8.41
Silico-Phosphate													
250	266	.156	0.80	5.13	.128	0.78	6.09	.146	1.13	7.74	.166	0.86	5.18

[1] Yield of four replicates composited for analysis.

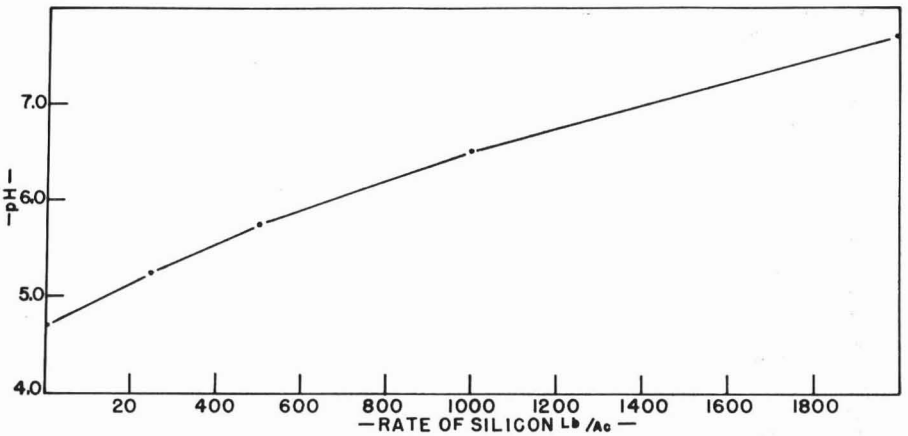

FIGURE 2. Effect of sodium metasilicate on the pH of Helemano soil. The soils were collected and analyzed for pH after termination of the second cutting in Field Experiment 1.

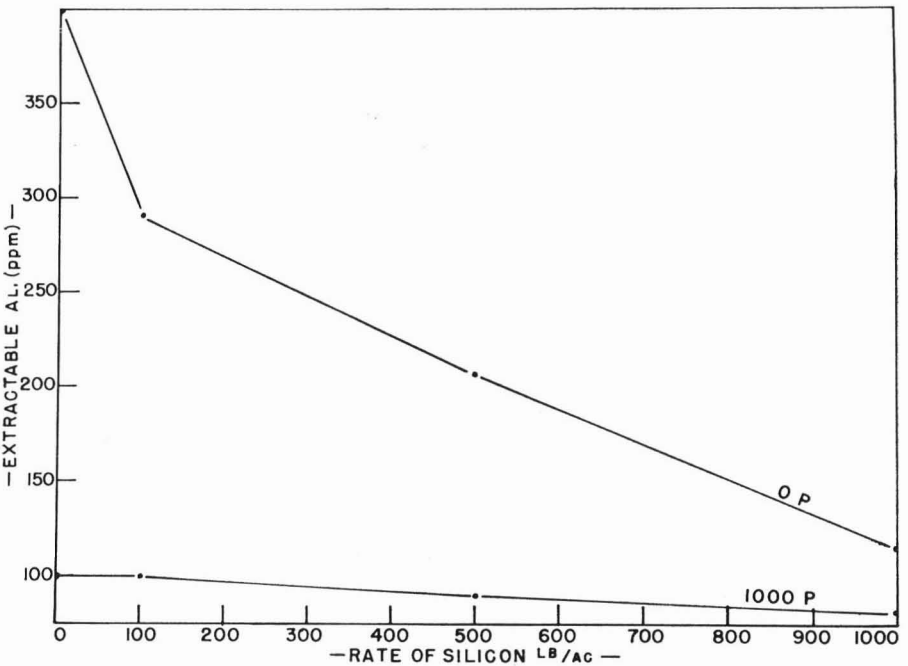

FIGURE 3. Effect of sodium metasilicate on the extractable aluminum content of Helemano soil. Sodium metasilicate added together with phosphorus shows a greater decrease in extractable aluminum than silicon applied alone (Pot Experiment 2).

TABLE 9. Soil analysis of Helemano soil treated with sodium metasilicate and dicalcium phosphate, after four cuttings of Sudan grass (Pot Experiment 2)[1]

TREATMENT, lb/acre			0.02 N H_2SO_4-EXTRACTABLE	$AlPO_4$,	SOLUBLE	EXTRACTABLE
P	Si	pH	P, ppm	P, ppm	Si, ppm	Al, ppm
0	0	6.80	40	29	33	400
0	100	6.40	41	27	36	285
0	500	6.68	38	25	48	210
0	1000	7.16	29	23	73	125
100	0	6.55	42	32	36	235
100	100	6.38	56	39	36	265
100	500	6.58	56	39	49	210
100	1000	6.78	40	39	59	165
500	0	6.45	151	195	49	185
500	100	6.60	182	136	46	120
500	500	6.50	199	124	48	140
500	1000	7.07	140	104	70	125
1000	0	6.55	411	338	83	100
1000	100	6.62	353	248	59	100
1000	500	6.70	353	232	70	85
1000	1000	6.90	344	244	85	70

[1] Soil from four replicates composited for analysis.

having demonstrated that Al plays a part in determining the shape of the silica solubility curves. The addition of Al to silica solutions showed a significant decrease in the silica concentration from pH 4.0 to 10.0, the pH being adjusted with NaOH. It is rather difficult to ascertain whether the decrease of Al resulted from the formation of an alumino-silicate compound or, which is more probable, from the formation of amorphous aluminum hydroxide. However, it is possible for silica and amorphous aluminum hydroxide to form complexes.

In most acid soils containing high amounts of active Al the rapid inactivation of Al following additions of alkaline materials such as lime, sodium silicate, sodium carbonate, calcium silicate, and so forth, increases the availability of phosphorus. The process by which P becomes more available involves equilibrium reactions, and the one most likely to occur under these conditions is the shift in equilibrium between amorphous hydrated aluminum oxide and variscite.

In Helemano pot experiment 2, the application of sodium metasilicate tended to decrease the $AlPO_4$ fraction at the higher P levels (table 9). In pot experiment 3, soils treated with calcium silicate or silica gel also showed a reduction in the $AlPO_4$ fraction. In addition, in pot test 3, the DCP applied alone showed 58 ppm P, and SP, applied alone, contained 54 ppm P associated with $AlPO_4$. In both pot tests, the silicated soils receiving 100 pounds P plus 1000 pounds Si per acre contained 39 ppm P as $AlPO_4$.

Chang and Jackson (1958) also demonstrated that a reduction in the aluminum phosphate fraction occurred as the pH increased with the further formation of calcium phosphates following lime applications. However, in the case where silica gel decreased the amount of $AlPO_4$ formed, it was associated with an unexpected decrease in the soil pH, which accordingly should have caused an increase in active Al concentration and P fixation. Perhaps the greater surface activity associated with colloidal silica inactivated the Al and P through a complex with silica, and thus less P was present as aluminum phosphate since the ionic equilibrium involving the Al and P ion species was reduced.

Silicon imparts only a slightly ionic character to soils, as noted by the small amounts of soluble silicon extracted at neutrality from treated soils. The silicon must be present in ionic form prior to measurement as silicomolybdate yellow color, leaving a considerable amount in nonionic (gel-like) form of silicon in the soil. Thus it is possible that a large amount of silica exists as gels or amorphous particles and is associated with Al and P in a weak state of atomic arrangement which diffuses as a complex in soil. Soluble silicates dissociate into cation and anion counterparts where the former causes a change in soil pH and the latter converts to silicic acid. The silicic acid subsequently stabilizes as amorphous silica gels.

EFFECT OF SILICON IN POAMOHO SOIL

Effect of sodium and calcium silicate on yield, phosphorus uptake, and chemical composition of Sudan grass grown on Poamoho soil. Three successive cuttings of Sudan grass grown on Poamoho soil, fertilized with one level of P combined with four levels of calcium silicate, produced very little change in crop yield (pot experiment 5). The slight depressions in yield in the DCP, CMP, DAP, and RP series when calcium silicate was applied are illustrated in table 10. Dry matter yields in the CSP series improved slightly when P was applied together with calcium silicate, but remained essentially unchanged in the No P series. However, in most cases, P uptake was increased by applications of silicon, applied as calcium silicate, up to 1000 pounds per acre (table 11). Applications of silicon greater than 1000 pounds per acre remained ineffective in increasing the P uptake. In all cases, the percentage of silicon and the Si/P ratio increased with increasing levels of calcium silicate (tables 12 and 13).

Sodium metasilicate depressed yield considerably at silicon rates similar to those of the calcium silicate series. The nonbeneficial effect of sodium silicate application to Poamoho soil has also been observed by Sherman *et al.* (1955). The detrimental effect of sodium metasilicate was attributed to the increased alkalinity produced by the Na ion when in a soil possessing a low buffering capacity. The Poamoho soil also has a higher total silica content than the Helemano soil. In these tests, soluble silicates applied to the Poamoho soil were nonbeneficial in improving P absorption and yield by Sudan grass.

TABLE 10. Pot trial on the effect of calcium silicate and of sodium metasilicate applied with various phosphate fertilizers on dry matter yield of Sudan grass grown on Poamoho soil

(Pot Experiment 5)[1]

TREATMENT, lb/acre		CALCIUM SILICATE Cutting				SODIUM METASILICATE Cutting			
P	Si	1	2	3	Total	1	2	3	Total
No P Series		*gm/pot*				*gm/pot*			
0	0	15.0	24.0	12.3	51.3	20.3	22.3	9.3	51.9
0	500	8.3	20.3	20.0	48.6	11.7	24.7	14.7	51.1
0	1000	9.7	24.0	18.0	51.7	—	—	—	—
0	2000	11.0	26.3	19.0	56.3	7.0	15.0	—	22.0
CSP Series									
250	0	37.7	33.0	18.3	89.0	38.3	29.0	18.7	86.0
250	500	31.7	35.3	22.3	89.3	38.7	28.3	11.0	78.0
250	1000	36.7	40.3	23.3	100.3	31.0	25.0	17.3	73.3
250	2000	32.7	38.7	22.0	93.4	9.7	25.0	—	34.7
CMP Series									
250	0	34.7	35.3	20.3	90.3	38.3	29.0	18.7	82.9
250	500	32.0	33.7	17.3	83.0	40.7	26.7	19.3	86.7
250	1000	32.7	35.0	20.7	88.4	28.3	24.7	18.7	71.7
250	2000	25.3	30.0	21.0	76.3	6.0	20.0	—	26.0
DAP Series									
250	0	39.3	31.3	21.3	91.9	54.3	30.3	15.7	100.3
250	500	42.0	26.7	14.7	83.4	50.7	28.3	15.7	94.7
250	1000	40.0	33.7	21.0	94.7	24.0	28.3	17.7	70.0
250	2000	37.7	36.3	17.7	91.7	17.0	21.7	—	38.7
DCP Series									
250	0	34.0	34.0	19.7	87.7				
250	500	34.0	26.7	20.7	81.4				
250	1000	33.0	30.0	19.7	82.7				
250	2000	26.3	32.3	15.3	73.9				
RP Series									
250	0	21.7	31.3	18.7	71.7				
250	500	14.0	30.7	20.3	65.0				
250	1000	12.3	28.0	21.0	61.3				
250	2000	9.3	28.3	24.3	61.9				
Growth Days		44	44	54		47	47	59	

[1] Treatments replicated four times.

Effect of silico-phosphate reaction product, with and without lime from various sources, on yield, phosphorus uptake, and chemical composition of Sudan grass grown on Poamoho soil. Sudan grass grown on Poamoho soil demonstrated increasing dry yield with successive increments of silico-phosphate reaction product until the application of P reached 1000 pounds per acre, after which the reaction product was no longer effective (pot experiment 4). Both the hydrated lime and nonlimed series showed similar

TABLE 11. Effect of calcium silicate and of sodium metasilicate applied with various phosphate fertilizers on phosphorus uptake by Sudan grass grown on Poamoho soil

(Pot Experiment 5)[1]

TREATMENT, lb/acre		CALCIUM SILICATE				SODIUM METASILICATE			
		Cutting				Cutting			
P	Si	1	2	3	Total	1	2	3	Total
No P Series		*P, mgm/pot*				*P, mgm/pot*			
0	0	18.9	19.2	10.6	48.7	17.5	17.8	8.0	43.3
0	500	12.3	16.2	17.2	45.7	14.0	27.7	19.1	60.8
0	1000	14.4	19.2	15.5	49.1	—	—	—	—
0	2000	16.3	21.0	19.4	56.7	9.5	21.6	—	31.1
CSP Series									
250	0	55.8	37.0	23.8	116.6	64.3	32.5	31.0	127.8
250	500	53.3	42.4	30.3	126.0	68.1	44.1	21.8	134.0
250	1000	61.7	52.4	33.6	147.7	54.6	41.5	31.5	127.6
250	2000	59.5	50.3	31.7	141.5	17.1	34.0	—	51.1
CMP Series									
250	0	50.0	33.9	24.4	108.3	48.3	37.1	27.7	113.1
250	500	40.3	37.7	25.6	103.6	68.4	42.7	32.8	143.9
250	1000	47.1	44.1	30.6	121.8	51.5	39.5	31.8	122.8
250	2000	49.1	24.0	33.6	106.7	12.6	34.0	—	46.6
DAP Series									
250	0	51.1	28.2	26.8	106.1	95.6	38.2	26.7	160.5
250	500	60.5	25.6	19.1	105.2	89.2	40.8	28.6	158.6
250	1000	64.0	37.7	28.6	130.3	47.5	40.8	30.1	118.4
250	2000	62.6	43.6	25.5	131.7	38.8	36.9	—	75.7
DCP Series									
250	0	53.0	34.7	25.6	113.3				
250	500	53.0	36.3	33.1	122.4				
250	1000	68.0	43.2	30.7	141.9				
250	2000	46.3	46.5	26.9	119.7				
RP Series									
250	0	24.3	26.9	20.2	71.4				
250	500	15.7	26.4	19.5	61.6				
250	1000	13.8	24.1	22.7	60.6				
250	2000	12.1	31.7	26.2	70.0				

[1] Yields of four replicates composited for chemical analysis.

yield responses (table 14). While hydrated lime did not increase the yield over unlimed soils, it increased the amount of P assimilated by the test crop at the heavier P rates. Reagent grade calcium silicate and TVA calcium silicate slag, applied to give equivalent neutralizing rates, produced yields similar to those of hydrated lime but showed a higher uptake of P (table 15). Phosphorus uptake was increased 20.6 percent, 27.7 percent, and 9.4 percent over nonlimed SP alone when calcium silicate, calcium silicate slag, and calcium hydroxide were used as liming agents, respective-

TABLE 12. Chemical composition of Sudan grass grown on Poamoho soil treated with various phosphate fertilizers and sodium metasilicate in pot trial (Pot Experiment 5)[1]

TREATMENT, lb/acre		CUTTING								
		First			Second			Third		
P	Si	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P
No P Series										
0	0	.086	0.52	6.05	.080	0.44	5.50	.086	0.51	5.93
0	500	.120	1.01	8.42	.112	0.79	7.05	.130	0.80	6.15
0	2000	.136	—	—	.144	1.07	7.43	—	—	—
CSP Series										
250	0	.168	0.39	2.32	.112	0.43	3.84	.166	0.52	3.13
250	500	.176	—	—	.156	0.86	5.51	.198	1.04	5.25
250	1000	.176	0.78	4.43	.166	0.80	4.82	.182	1.34	7.36
250	2000	.176	1.51	8.58	.136	1.12	8.24	—	—	—
CMP Series										
250	0	.126	0.36	2.86	.136	0.42	3.09	.160	0.50	3.13
250	500	.168	0.83	4.94	.160	0.74	4.63	.170	0.94	5.53
250	1000	.182	1.01	5.55	.160	1.05	6.56	.170	1.48	8.71
250	2000	.210	2.10	10.00	.170	1.35	7.94	—	—	—
DAP Series										
250	0	.176	0.30	1.70	.126	0.44	3.49	.170	0.63	3.71
250	500	.176	0.65	3.69	.144	0.88	6.11	.182	1.14	6.26
250	1000	.198	0.81	4.09	.144	1.03	7.15	.170	1.63	9.59
250	2000	.228	2.25	9.87	.170	1.19	7.00	—	—	—

[1] Treatments replicated four times; yields composited for chemical analysis.

ly. The phosphorus present in the slag represents an extra increment of P and was not included in the treatment rate. When silica gel was supplemented together with SP and calcium hydroxide to increase the application level of silicon to 2000 pounds per acre, both dry matter yield and P uptake were considerably improved. The P uptake was increased 36 percent and the yield about 25 percent over SP and $Ca(OH)_2$ alone. This boost in performance suggests that here there is an interrelationship operating between the P, Si, and Ca materials which merits further investigation.

EFFECT OF SILICON IN KAPAA SOIL

Effect of silicates on yield, phosphorus uptake, and chemical composition of Sudan grass grown on Kapaa topsoil and stripsoil. Results from a phosphate-silicate field experiment (field experiment 2) on Kapaa topsoil in the Bauxite Reclamation Area proved rather inconclusive due to lime contamination of the soil. A large portion of the test showed unusually high yield variation; the error involved in statistical analysis of the yield data was such that the L.S.D. values at the 5 percent and 1 percent levels were so large as to mask any possible responses to added silicates (table 16).

TABLE 13. Chemical composition of Sudan grass grown on Poamoho soil treated with various phosphate fertilizers and calcium silicate in pot trial (Pot Experiment 5)[1]

TREATMENT, lb/acre		CUTTING								
		First			Second			Third		
P	Si	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P
No P Series										
0	0	.126	0.60	4.76	.080	0.46	5.75	.086	0.49	5.70
0	500	.148	1.41	9.53	.080	0.83	10.38	.086	0.72	8.37
0	1000	.148	1.79	12.09	.080	1.27	15.88	.086	0.91	10.58
0	2000	.148	1.94	13.11	.080	1.51	18.88	.102	0.53	5.20
CSP Series										
250	0	.148	0.43	2.91	.112	0.53	4.73	.130	0.51	3.92
250	500	.168	0.79	4.70	.120	0.79	6.58	.136	0.79	5.81
250	1000	.168	1.13	6.73	.130	1.15	8.85	.144	1.00	6.94
250	2000	.182	1.58	8.68	.130	1.33	10.23	.144	1.25	8.68
CMP Series										
250	0	.156	0.42	2.69	.102	0.43	4.22	.130	0.52	4.00
250	500	.156	0.94	6.03	.136	0.81	5.96	.160	0.59	3.69
250	1000	.206	1.43	6.94	.144	1.02	7.08	.156	1.24	7.95
250	2000	.176	1.46	8.30	.144	1.25	8.68	.176	1.57	8.92
DAP Series										
250	0	.144	0.50	3.47	.096	0.55	5.73	.120	0.50	4.17
250	500	.126	0.87	6.90	.112	0.79	7.05	.148	0.72	4.86
250	1000	.144	1.01	7.01	.126	1.07	8.49	.148	0.99	6.69
250	2000	.194	1.68	8.66	.080	1.24	15.50	.160	1.31	8.19
DCP Series										
250	0	.130	0.39	3.00	.090	0.54	6.00	.126	0.49	3.89
250	500	.144	0.80	5.56	.096	0.79	8.23	.130	0.81	6.23
250	1000	.160	1.12	7.00	.112	0.98	8.75	.136	0.93	6.84
250	2000	.166	1.21	7.29	.120	1.36	11.33	.144	1.50	10.42
RP Series										
250	0	.112	0.47	4.20	.086	0.54	6.28	.108	0.51	4.72
250	500	.112	1.20	10.71	.086	0.83	9.65	.096	0.61	6.35
250	1000	.112	1.45	12.95	.086	1.06	12.33	.108	0.96	8.89
250	2000	.130	1.99	15.31	.112	1.20	10.71	.108	1.14	10.56

[1] Treatments replicated four times; yields composited for chemical analysis.

Younge and Moomaw (1960), in establishing fertility experiments at the same site, explained the coral sand contamination as originating from coral ballast on former roadways used by the military during World War II.

No statistically significant yield changes were noted in the topsoil experiment in any of the phosphate series except in the case of the highest level of silicon applied as sodium silicate; here yields were greatly depressed because of the high Na content of the silicate material. Germination of Sudan grass was suppressed at the two highest levels of silicon and measures were not taken to completely reseed these plots. In the RP series, more P

TABLE 14. Pot trial on the effect of silico-phosphate reaction product applied with and without hydrated lime and other lime sources on yield and phosphorus uptake by Sudan grass grown on Poamoho soil

(Pot Experiment 4)[1]

TREATMENT, lb/acre		DRY MATTER YIELD, gm/pot				PHOSPHORUS UPTAKE, mgm/pot			
		Cutting				Cutting			
P	Si	1	2	3	Total	1	2	3	Total
No Lime Series									
0	0	10.7	24.0	15.0	49.7	15.8	19.2	13.5	48.5
250	266	32.7	29.0	13.3	75.0	39.2	31.3	16.8	87.3
500	533	36.7	31.7	14.3	82.7	41.1	35.5	20.6	97.2
750	799	40.3	28.7	18.0	87.0	70.9	37.3	29.9	138.1
1000	1066	46.3	31.7	16.3	94.3	101.9	50.7	30.6	183.2
2000	2132	34.7	37.0	19.7	91.4	102.0	77.7	41.4	221.1
Lime Series[2]									
0	0	10.3	24.7	15.0	50.0	13.4	22.2	15.3	50.9
250	266	31.7	31.0	14.7	77.4	39.9	34.7	21.8	96.4
500	533	35.7	27.0	17.0	79.7	57.1	42.1	29.9	129.1
750	799	43.3	31.7	16.0	91.0	90.9	49.5	30.1	170.5
1000	1066	49.7	35.7	18.3	103.7	131.2	60.0	36.2	227.4
2000	2132	44.7	33.7	15.0	93.4	155.6	82.2	35.7	273.5
Other Lime Sources									
250	2153[3]	27.7	29.5	17.7	74.9	37.7	46.0	26.2	109.9
250	955[4]	38.0	24.0	17.0	79.0	59.3	32.6	28.9	120.8
250	2000[5]	43.0	41.0	19.0	103.0	67.1	55.8	28.1	151.0
Growth Days		43	45	47					

[1] Treatments with four replications, composited for analysis.

[2] Brought to pH 6.2 with hydrated lime.

[3] Brought to pH 6.2 with calcium silicate.

[4] Brought to pH 6.2 with calcium silicate slag.

[5] Silicon rate to 2000 with silica gel supplemented with hydrated lime to pH 6.2.

was assimilated by the test crop with increasing levels of silicon. It was evident, however, that even after four cuttings, the total amount of P utilized was negligible when compared to the amount applied. The recovery of P from the phosphate fertilizers applied to these soils is therefore quite low, and the presence of silicon does not induce a greater attainment in efficiency.

Younge and Moomaw (1960) found that the maximum response to Sudan grass yield was obtained on plots receiving 1000 pounds P per acre and that fairly satisfactory yields occurred at levels of P at 500 pounds per acre, and above. It is obvious from their results that a relatively large quantity of P is needed to satisfy the fixing capacity of the soil system. The yields obtained in the DCP series on stripsoil showed silica to be without effect in the first and second cuttings, but yields improved in the third and

TABLE 15. Chemical composition of Sudan grass grown on Poamoho soil treated with various rates of silico-phosphate reaction product with and without lime in pot trial

(Pot Experiment 4)[1]

TREATMENT, lb/acre		CUTTING								
		First			Second			Third		
P	Si	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P
No Lime Series										
0	0	.148	.72	4.86	.080	0.65	8.13	.090	0.59	6.56
250	266	.120	.50	4.17	.108	0.76	7.04	.126	0.78	6.19
500	533	.112	.43	3.84	.112	0.76	6.79	.144	0.86	5.97
750	799	.176	.65	3.69	.130	0.79	6.08	.166	0.97	5.84
1000	1066	.220	.65	2.95	.160	0.93	5.81	.188	1.07	5.69
2000	2132	.294	.81	2.76	.210	1.06	5.05	.210	1.09	5.19
Lime Series										
0	0	.130	.48	3.69	.090	0.51	5.67	.102	0.59	5.78
250	266	.126	.36	2.86	.112	0.51	4.55	.148	0.75	5.07
500	533	.160	.45	2.81	.156	0.87	5.58	.176	0.94	5.34
750	799	.210	.56	2.67	.156	0.94	6.03	.188	1.12	5.96
1000	1066	.264	.71	2.69	.168	0.93	5.54	.198	0.97	4.90
2000	2132	.348	.93	2.67	.244	1.46	5.98	.238	1.58	6.64
Other Lime Sources										
250	2153	.136	1.25	9.19	.156	1.56	10.00	.148	1.67	11.28
250	955	.156	0.55	3.53	.136	0.93	6.84	.170	0.98	5.76
250	2000	.156	1.37	8.78	.136	1.52	11.18	.148	1.56	10.54

[1] Treatments replicated four times; yields composited for chemical analysis.

fourth cuttings. Yields were generally depressed at levels of silicon greater than 1000 pounds per acre; this consequence is attributed to the lethal effect of the Na element on seed germination, thus causing a poor crop stand. The silico-phosphate reaction product showed superior performance over dicalcium phosphate when applied at 1000 pounds per acre. It is evident, however, that, at lower levels, SP was not able to promote growth of Sudan grass much more than DCP plus silicon when applied to the stripsoil. In general, yield was in agreement with Younge and Moomaw (1960), who found that initial stripsoil yields were lower than topsoil yields but that they improved rapidly with successive cuttings.

Chemical analysis of composited whole plant tissue revealed that, in general, P became more available with time in both the presence and absence of silicon (table 17). This behavior is a function perhaps of rainfall since the silicon content also increased with time. The total P uptake cannot be compared by this measure since depressed yields in most cases showed a higher P content. The Si/P ratio increased with silicon application but was dependent on the stage of maturity of the test crop. The ratios obtained under field conditions were also generally lower than those obtained in pot experiments.

TABLE 16. Field trial on the effect of sodium metasilicate on yield and phosphorus uptake from three phosphate fertilizers by Sudan grass grown on Kapaa soil, topsoil, and stripsoil; four cuttings

(Field Experiment 2, topsoil, and Experiment 3, stripsoil)[1]

TREATMENT, lb/acre		DRY MATTER YIELD, lb/acre					PHOSPHORUS UPTAKE, lb/acre				
		Cutting					Cutting				
P	Si	1	2	3	4	Total	1	2	3	4	Total
No P Series — Top											
0	0	914	1128	962	2024	5,028	1.17	2.14	1.69	4.17	9.17
0	250	1565	1493	1095	1527	5,680	2.57	2.84	1.75	3.02	10.18
0	1000	1015	863	1095	2124	5,097	1.66	1.47	2.06	3.61	8.80
DCP Series — Top											
500	0	3320	4016	2788	2987	13,111	4.45	7.87	5.52	8.30	26.14
1000	0	3213	4248	2390	2390	12,241	4.18	7.99	6.64	9.66	28.47
500	250	3068	3219	2124	3120	11,531	3.87	5.47	6.41	10.42	26.17
500	500	2755	4348	2456	3651	13,210	3.58	7.39	7.12	10.37	28.46
500	1000	1267*	2721*	2356	3020	9,364	1.62	5.12	5.23	8.58	20.55
500	2000	250**	1162**	631**	730**	2,773	0.55	1.86	1.40	2.25	6.06
AP Series — Top											
500	0	5552	5874	3485	3584	18,495	7.00	8.46	6.55	7.96	29.97
1000	0	6727	4978	3352	3452	18,509	12.92	9.86	6.64	7.66	37.08
500	250	5820	6206	2921	3120	18,067	6.52	7.82	6.13	8.67	29.14
500	500	5436	5111	2755	3783	17,085	6.96	9.71	6.56	11.65	34.88
500	1000	3611*	4945	2655	3352	14,563	4.69	10.68	6.05	8.58	30.00
500	2000	1063**	2124**	896**	1294**	5,377	1.38	3.61	2.04	3.24	10.27
RP Series — Top											
500	0	203	962	863	2224	4,252	0.22	1.42	1.52	3.47	6.63
1000	0	450	1062	1493	2323	5,328	0.59	1.76	2.39	4.51	9.25
500	250	1051	1128	1294	2091	5,564	1.26	1.67	2.69	3.68	9.30
500	500	939	996	929	2423	5.287	1.31	1.75	1.93	4.26	9.25
500	1000	1518	1759	1593	2589	7,459	2.25	2.92	3.09	3.83	12.09
500	2000	808	1029	830	996	3,663	1.26	1.98	1.51	1.75	6.50
L.S.D. at .05*		1770	1174	1088	1513	5,545					
level .01**		2346	1554	1440	2003						

(Continued)

TABLE 16. *Continued*

TREATMENT, lb/acre		DRY MATTER YIELD, lb/acre					PHOSPHORUS UPTAKE, lb/acre				
		Cutting					Cutting				
P	Si	1	2	3	4	Total	1	2	3	4	Total
Growth Days		52	48	52	71						
DCP Series — Strip											
0	0	250	1394	1759	1128	4,531	0.55	1.56	1.69	1.26	5.06
500	0	2092	4190	3252	1394	10,928	3.77	5.45	5.07	2.93	17.22
1000	0	2343	3485	3352	2555	11,735	4.22	5.44	5.56	4.34	19.56
500	250	1396	3651	3617	3717	12,381	2.88	5.40	5.21	5.35	18.84
500	500	1166	3452	3983	3385	11,986	2.19	5.11	5.74	5.75	18.79
500	1000	0	1925	2157	2721	6,803	0.00	2.85	2.72	3.54	9.11
500	2000	0	0	133	232	365	0.00	0.00	0.21	0.30	0.51
SP — Strip											
1000	1085	3440	4547	3584	2788	14,359	4.30	7.73	5.59	5.24	22.86

[1] Treatments with six replications; yields composited for analysis.

TABLE 17. Chemical composition of Sudan grass plant tissue grown at the Bauxite Reclamation Area on Kapaa topsoil and stripsoil under various phosphate-silicate treatments

(Field Experiment 2, topsoil, and Experiment 3, stripsoil)[1]

TREATMENT, lb/acre		CUTTING											
		First			Second			Third			Fourth		
P	Si	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P	% P	% Si	Si/P
No P Series — Top													
0	0	.128	.05	0.39	.190	.10	0.53	.176	.06	0.34	.206	.11	0.53
0	250	.164	.09	0.55	.190	.15	0.79	.160	.15	0.94	.198	.21	1.06
0	1000	.164	.10	0.61	.170	.16	0.94	.188	.21	1.12	.170	.47	2.76
DCP Series — Top													
500	0	.134	.08	0.60	.196	.10	0.51	.198	.10	0.51	.278	.21	0.76
1000	0	.130	.07	0.54	.188	—	—	.278	.10	0.36	.404	.14	0.35
500	250	.126	.10	0.79	.170	.15	0.88	.302	.26	0.86	.334	.45	1.35
500	500	.130	.11	0.85	.170	.14	0.82	.290	.31	1.07	.284	.48	1.69
500	1000	.128	.09	0.70	.188	.17	0.90	.222	.30	1.35	.284	.54	1.90
500	2000	.220	.36	1.64	.160	.20	1.25	.222	.35	1.58	.308	.70	2.27
AP Series — Top													
500	0	.126	.09	0.71	.144	.07	0.49	.188	.06	0.32	.222	.15	0.68
1000	0	.192	.10	0.52	.198	—	—	.198	.08	0.40	.222	.14	0.63
500	250	.112	.13	1.16	.126	.15	1.19	.210	.25	1.19	.278	.41	1.47
500	500	.128	.12	0.94	.190	.27	1.42	.238	.37	1.55	.308	.63	2.05
500	1000	.130	.10	0.77	.216	.21	0.97	.228	.30	1.32	.256	.69	2.70
500	2000	.130	.12	0.92	.170	.22	1.29	.228	.35	1.54	.250	.65	2.60
RP Series — Top													
500	0	.108	.15	1.39	.148	.14	0.95	.176	.13	0.74	.156	.38	2.44
1000	0	.130	.09	0.69	.166	—	—	.160	.08	0.50	.194	.11	0.57
500	250	.120	.14	1.17	.148	.12	0.81	.208	.08	0.38	.176	.41	2.33
500	500	.140	.12	0.86	.176	.19	1.08	.208	.26	1.25	.176	.58	3.30
500	1000	.148	.08	0.54	.166	.19	1.74	.194	.25	1.29	.148	.49	3.31
500	2000	.156	.21	1.35	.192	.14	0.73	.182	.19	1.04	.176	.53	3.01
DCP Series — Strip													
0	0	.220	.08	0.36	.112	.14	1.25	.096	.16	1.67	.112	.23	2.05
500	0	.180	—	—	.130	.16	1.23	.156	.18	1.15	.210	.29	1.38
1000	0	.180	.09	0.50	.156	—	—	.166	.18	1.08	.170	.26	1.53
500	250	.206	.19	0.92	.148	.34	2.30	.144	.29	2.01	.144	.46	3.19
500	500	.188	.26	1.38	.148	.36	2.43	.144	.43	2.99	.170	.64	3.76
500	1000	—	—	—	.148	.14	0.95	.126	.33	2.62	.130	.65	5.00
500	2000	—	—	—	—	—	—	.156	.53	3.40	.130	.86	6.62
SP — Strip													
1000	1085	.125	.13	1.04	.170	.63	3.71	.156	.65	4.17	.188	.72	3.83

[1] Treatments replicated six times; yields composited for chemical analysis. The ratoon crops received no additional nitrogen fertilizer and foliar deficiency ensued.

SUMMARY

The high phosphorus-fixing capacity of the Hawaiian soils is attributed primarily to the presence in these soils of high amounts of amorphous aluminum, iron, and titanium, as well as allophanic and halloysitic clay minerals. This phenomenon of phosphorus fixation has caused inefficient use of phosphates added as fertilizers and has been, apparently, the primary cause of low crop response to phosphorus.

Soils representing three main latosolic groups in the Hawaiian Islands were used in studying phosphorus-silicon interactions. Low Humic Latosol, Humic Latosol, and Aluminous Ferruginous Latosol soils, each possessing distinct differences in morphology and mineral composition, were found to pose interactions upon silicate additions that were beneficial in some cases and harmful in others. Both the high silicon representative of the Low Humic Latosol (Poamoho soil) and the low silicon representative, Aluminous Ferruginous Latosol (Kapaa soil), showed no beneficial response when various soluble silicates were applied together with phosphates, but significant changes in yield and phosphorus uptake were obtained in the siliceous (15 to 25 percent SiO_2) Humic Latosol (Helemano soil).

The dry matter yield of Sudan grass grown on Helemano soil was three times greater when soluble silicon was applied with phosphorus than when phosphorus was applied alone. Soluble silicate treatments alone also showed better yield performance than the controls. The form of the water-soluble phosphate fertilizer utilized determined the magnitude of the silicon benefit on yields; i.e., the less soluble phosphates produced greater yield increases than did the more soluble phosphates when applied together with silicon. Dicalcium phosphate and rock phosphate improved dry matter yields in the first and second cuttings, but ammonium phosphate improved yield only in the first cutting. When sodium metasilicate was applied alone at 1000 pounds per acre, 76 percent more phosphorus was assimilated by the test crop than by the control. Similar effects were also noted in the presence of phosphates, but the degree of assimilation was dependent on the water-soluble phosphorus content. On a percentage basis, rock phosphate, the least soluble agent, released more phosphorus than the highly soluble ammonium phosphate released over controls. Dicalcium phosphate was intermediate in supplying phosphorus in the presence of sodium metasilicate. However, even after two harvestings of Sudan grass, the amount of phosphorus taken up compared with that remaining in the soil was negligible. Apparently, the phosphorus-fixing capacity of the soil remained unsatisfied with respect to phosphorus at the deficient level of application. Perhaps silicon enhanced availability of the phosphorus by reducing the fixing capacity or by substituting for phosphorus in the soil system. This could explain the higher percentage of performance of the less soluble phosphorus carriers over highly soluble phosphorus in the presence of soluble silicates.

A change in the pH of the soil occurred upon application of sodium metasilicate, calcium silicate, or silica gel. Soluble silicates caused increases

in pH whereas colloidal silica produced the opposite effect. The liming effect of sodium metasilicate was attributed to the hydrolysis of the material into sodium hydroxide and silicic acid. As was expected, the slightly less soluble calcium silicate was less effective than sodium metasilicate in changing the pH of the soil. The colloidal silica perhaps decreased the pH by releasing silicic acid to the soil. A greater change in pH occurred in the least buffered of the soil systems, such as the Poamoho soil. The detrimental effect caused by the increased concentration of sodium ions at high rates resulted in depressed yields due to soil deflocculation and water-logging and to loss of seedlings on germination.

An inverse relationship between sodium metasilicate application and extractable aluminum was found to exist in the Helemano soil. The magnitude of the effect was greatest when the soluble silicate was applied alone. Although the tests also illustrated that dicalcium phosphate at 1000 pounds per acre of P applied with different levels of silicon caused a significant decrease in the aluminum concentration, the effectiveness of the silicate was less than when it was applied alone. The beneficial response in yield, which follows silicon application, can be attributed in part to the reduction in aluminum if the aluminum is in fact present in toxic amounts, but this will not completely explain the greater availability of phosphorus associated with such applications.

The soil representatives of the Low Humic Latosol (Poamoho) and the Aluminous Ferruginous Latosol (Kapaa) showed nonbeneficial effects from silicon applications. Because only Humic soils were found readily responsive, indications are that the area of use of silicon in increasing phosphorus efficiency may be limited. Furthermore, the benefits from added silicon may be controlled by other cations in the soil system.

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